SPACE CHARGE EFFECTS IN A LASER-FIBER OPTICS TRIGGERED MUTICHANNEL SPARK GAP*

H.C. Harjes, E.E. Kunhardt, and M. Kristiansen
Department of Electrical Engineering
Texas Tech University
Lubbock, Texas 79409 USA
and
L.L. Hatfield
Department of Physics
Texas Tech University
Lubbock, Texas 79409 USA
and
A.H. Guenther
Air Force Weapons Laboratory
Kirtland Air Force Base
Albuquerque, NM 87117 USA

Abstract

The dual channel triggering of a spark gap switch by ruby laser radiation is discussed. The spark gap is the output switch of a 20 ns, water dielectric Blumlein. The Blumleim is pulse charged in approximately 250 ns by a 3 stage Marx bank to 150 kV. The spark gap is operated at a pressure of 2540 Torr with a mixture of A and N_2 gas and an electrode separation of 2 cm. Two 1 mm diameter quartz optical fibers are used to transport two, 2 MW laser beams into the spark gap onto target points 6 cm apart. The two beams are obtained by optically splitting the output of a single laser. Under appropriate conditions, two arc channels are initiated by the laser beams along their paths. A small improvement in current risetime for dual channel events over single channel events is observed. Moreover, the number of successful dual channel events is observed to depend on the time of laser entry with reference to the beginning of the charging pulse, and on the gap polarity. The correlation of this behavior to the space charge build up in the slightly overvolted gap is discussed.

I. Introduction

The use of an optical fiber to transport a ruby laser pulse of sufficient power to trigger a high voltage spark gap has been reported earlier.[1] The results of this investigation show that the fiber imposes an upper limit on the laser power density that can be transported into the gap. For the fiber used in that investigation, the limit was approximately $3 \cdot 10^8$ W/cm^2. The dual channel triggering of a spark gap with laser power densities this low has, to our knowledge, not been reported. Since this laser power density level is a few orders of magnitude lower than levels previously used in dual channel laser triggering experiments,[2] it is important to ascertain whether two laser produced space charge concentrations are able to develop into two separate channels. For low power density levels, the space charge produced by the laser is small and the statistics of the subsequent avalanche development may prevent two sharing channels from developing.

Although the probability was low, it was observed in earlier experiment[1] that under certain conditions a second channel could be initiated by the laser. The spark gap switch in the experiment of reference 1 was pulse charged so that self-breakdown would occur in approximately 300 ns. The laser was to be fired so that the gap triggered before self-breakdown could occur. However, on some occasions the laser would fire late and initiate an arc channel in the gap even though a spontaneous channel had already begun elsewhere in the gap. Streak photographs of such occurrences are given in reference 1. This indicates that at a laser power density of $1.3 \cdot 10^8$ W/cm^2, the laser power density transported into the gap in reference 1, is high enough to initiate an arc channel even through another channel is forming elsewhere in the gap. The experiment described in this paper was carried out to investigate the possibility of using two fiber transmitted laser beams to initiate dual channel triggering of a spark gap switch.

It has been observed that the initiation of two channels dependes on the time of laser entry and on the polarity of the gap with respect to the direction of laser entry. Moreover, it was observed that the amplitude of the load current pulse increased with the number of channels. After a description of the experimental arrangement in Section II, a discussion and explanation of these observations is given in section III. Concluding remarks are given in Section IV regarding application of the scheme.

II Experimental Arrangement

The arrangement for this experiment is depicted in Fig. 1. The spark gap is the switch on the 20 ns, water dielectric, coaxial, Blumlein generator. The generator is matched to a 13 Ω load and has a capacitance of 6 nF. The intermediate conductor of the generator is pulse charged by a 3 stage, 300 kV, 2700 J, Marx bank. A capacitive voltage divider probe for monitoring the gap voltage is located in the Blumlein near the gap (Fig. 1). A resistive voltage divider probe for monitoring the load current is located in the Blumlein load resistor (Fig. 1). The spark gap parameters for this experiment are: electrode separation, 2 cm; pressure, 2540 Torr; gas mixture, 10% A - 90% N_2.

The triggering laser pulse is obtained from a ruby laser with active (Pockels cell) Q-switching. A typical pulse has an energy of 120 mJ with a full width at half maximum of between 20 and 30 ns. The laser pulse is monitored on each shot by a photodiode, as shown in Fig. 1. A 5 V, 3 ns pulse, derived from the output of the photodiode, is used to determine when the laser is fired. To get the two laser beams required for dual channel triggering, the output beam is split, as shown in Fig. 2. The angle between the beam splitter and the incident laser beam is adjusted until the transmitted and reflected beam energies, as measured by an optical energy meter, are essentially equal. The reflected beam is then redirected by a mirror so that both beams can be focussed onto two optical fibers, as shown in Fig. 2. The optical fibers are single element quartz fibers with numerical

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14. ABSTRACT
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15. SUBJECT TERMS

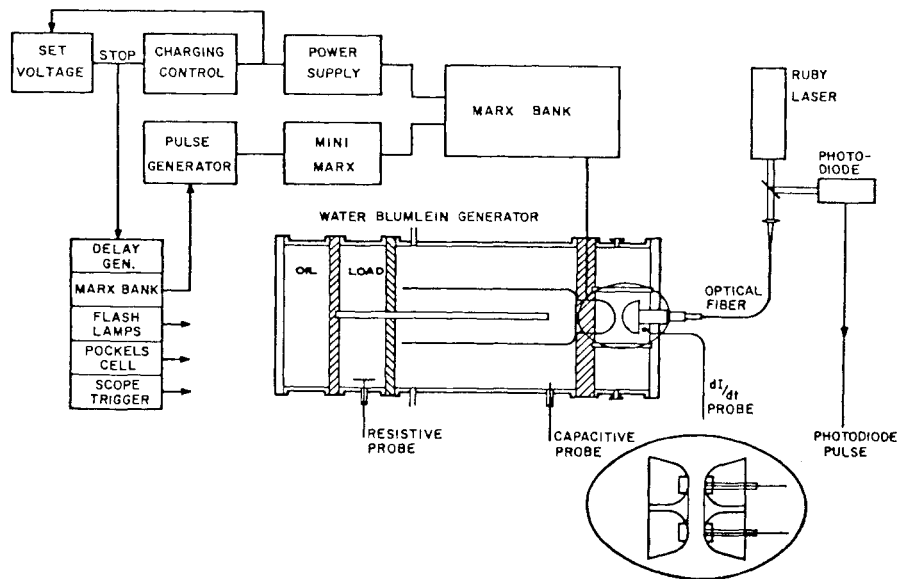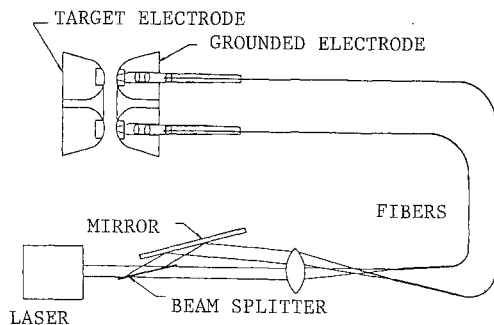| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Fig. 1   Experimental Arrangement
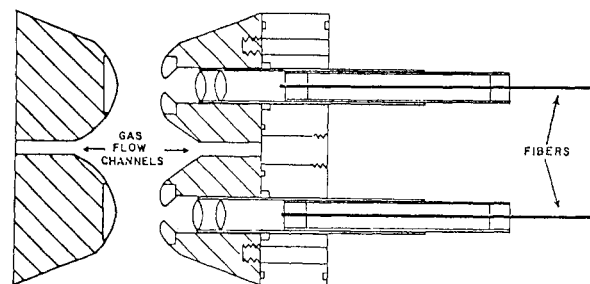

Fig. 2 Optics

Fig. 3   Output Optics and Electrodes

apertures of 0.22, diameters of 1 mm, and lengths of 1 m. The laser light exits the fibers with a divergence angle of 18°. An image of the fiber end, magnified by 1.5, is projected onto the target electrode (Fig. 3). The light enters the spark gap chamber through a 6.35 mm hole in a tungsten insert in the grounded brass electrode. It is then imaged onto a tungsten insert in the charged brass electrode. The optical system efficiency is 62%. On every shot, the breakdown mode (i.e. self-breakdown, single channel triggered breakdown, or dual channel breakdown) is determined from streak and time integrated photographs. The switching delay and current risetime are determined from an oscilloscope trace showing the 3 ns reference pulse and the load current pulse.

III. Results

A cross section of the electrodes used in this experiment is shown in Fig. 3. The electrodes were designed so that the maximum field in the gap occured at the laser target points.

The dual channel phenomenon observed in reference 1, occurred when the target electrode was positively charged and when the laser was fired just before self-breakdown was expected to occur. Thus, an attempt to observe dual channel triggering under these conditions was made. The target electrode was charged to +150 kV.

At this voltage, self-breakdown was observed to occur about 350 ns after the onset of charging. The gap was triggered by the laser, but no dual channel events were observed. In an effort to observe a dual channel event, the laser firing time was varied. The laser firing time is always measured with respect to the onset of the Blumlein charging. As the laser firing time was decreased (made earlier) dual channel events were observed. The occurence of a dual channel event at any particular laser firing time is random, with the probability increasing as the laser firing time decreased. This is shown in Fig. 4. In order to understand this result, the conditions in the gap at the time of laser entry must be considered.

Avalanche processes, initiated by random electrons create space charge in the gap. Since the appearence of electrons in the gap is random, the resulting charge distribution will also be random. In this experiment, voltage is applied to the gap long before the laser is fired. Thus, a random distribution of charge is always present in the gap when the laser enters. When the laser beams strike the target electrode, plasmas are produced. Since the target electrode is positively charged, the electrons in the plasmas are drawn into the electrode, leaving a positive space charge behind. The subsequent evolution of the space charge in the gap is determined by both the laser induced space charge and the already present random charge distribution. The quantity of space charge produced by the laser
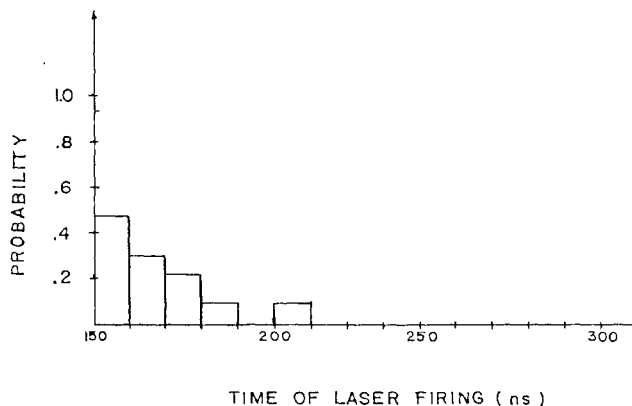
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TIME OF LASER FIRING (ns)

Fig. 4   Probability of Dual Channel Events vs Laser
         Firing Time for Positive Target Electrode
         Polarity

TIME OF LASER FIRING (ns)
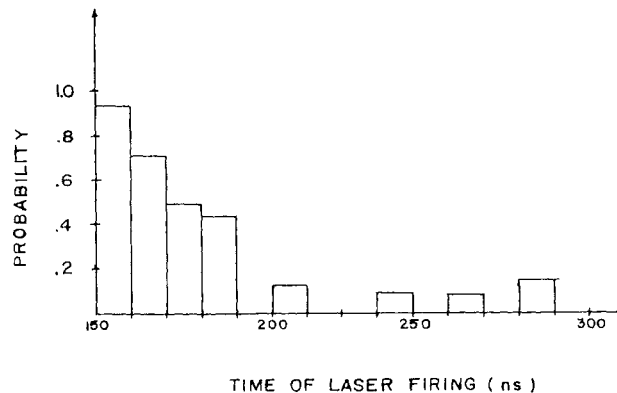
Fig. 5   Probability of Dual Channel Events vs. Laser
         Firing Time for Negative Target Electrode
         Polarity

the gap is larger than the quantity of the random
space charge already present when the laser enters
since the gap is always laser triggered. Thus, the
already present space charge constitutes a random
perturbation, which influences the further develop-
ment of the laser induced space charge. This ulti-
mately affects the formation of the arc channels. If
one channel bridges the gap well ahead of the other
channel, the other channel will be shorted out. Thus,
the size of the random perturbation (i.e. the relative
quantity of random space charge as compared to the
quantity of laser induced space charge) determines
whether or not a dual channel event will occur. If
the laser is fired earlier, the perturbation is made
smaller; thus, increasing the probability for dual
channel formation. This explains the results of Fig.
4   The fact that the target electrode is positive
makes the perturbation more pronounced, since the size
of the laser produced space charge is not enhanced by
avalanche multiplication processes. This suggests
that a negative target electrode polarity would be
more suitable to dual channel triggering. In such a
case, the electrons produced by the laser would be
accelerated across the gap; thus, enhancing the laser
produced space charge by a factor of $\exp(\alpha d)$. Con-
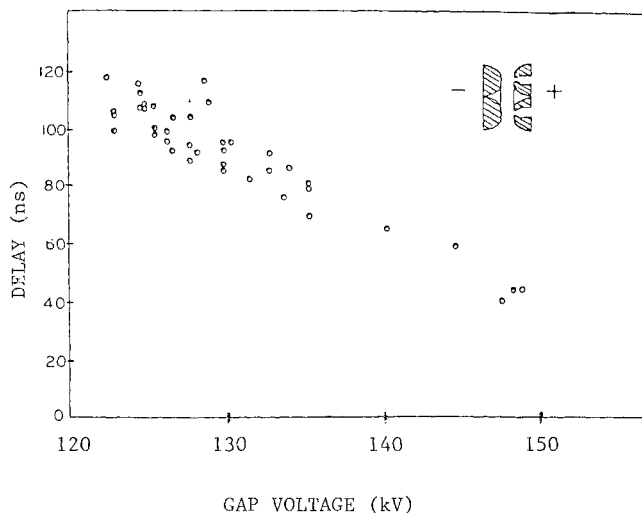sequently, the random charge distribution in the gap
would have a smaller effect.

In order to check this hypothesis, the gap polar-
ity was reversed and the experiment was repeated. Fig-
ure 5 shows how the probability of observing a dual
channel event depends upon the laser firing time for
a negative target electrode. Note that indeed, dual
channel events are more likely to occur when the tar-
get electrode is negatively charged; thus, supporting
the hypothesis. At the earlier laser firing times,
dual channel events were observed with a probability
close to 1. Figure 6 shows how the switching delay
varies with the voltage across the gap at the time of
laser firing for dual channel events and a negative
target electrode. When the laser is fired early so
that dual channel breakdown is more likely to occur,
the switching delay is greater than 100 ns and the
jitter, statistical variation in delay, is quite large.

After dual channel events were consistantly
achieved, a comparison of current risetimes for dual
and single channel events was made. The results of
several measurements showed that the average current
risetimes for the two cases were within 2%. Since
the uncertainty in the measurement was of this order,
no conclusions can be made about the risetimes. The
0 - 90% risetime for the current pulse was:

$$\tau \simeq 30 \text{ ns.}$$

GAP VOLTAGE (kV)

Fig. 6   Switching Delay vs. Voltage Across the Gap
         at the Time of Laser Firing

Six traces corresponding to six consecutive shots are
shown in Fig. 7. The first five result from dual
channel events and the last results from a single
channel event. A comparison of these traces reveals
that a significant difference in pulse heights exists
between the single and dual channel waveforms. Dual
channel pulses consistantly rise to a value 9% higher
than do single channel pulses. This result may be ex-
plained using a simple circuit model for the gap. The
spark gap, after closing, is modeled as an inductance
in series with a resistance, as shown in Fig. 8.

This inductance, L, is the sum of the inductance due
to the electrodes, L_e, (which is the same for both
cases) and the inductance due to the discharge, L_d,
(which is not the same for both cases). The rising
phase of the voltage across the Blumlein generator load
resistor is given by:

$$V = V_0 \frac{Z_0}{R+Z_0} \left[1 - e^{-\left[\frac{R+Z_0}{L}\right]t} \right] \tag{1}$$
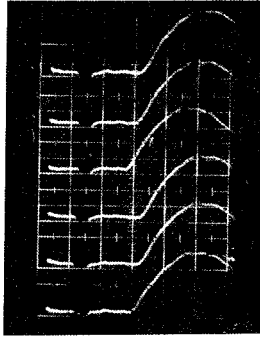
Fig. 7   Photograph of Six Consecutive Current
         Pulse Traces (20 ns/ div)

where, V_0 = charging voltage, $Z_0 = 6\Omega$, and R = dis-
charge resistance. Notice that the pulse height de-
pends upon the discharge resistance. The ratio of
pulse heights (as measured from several traces) is:

$$\frac{H_1}{H_2} = \frac{\text{single channel pulse height}}{\text{dual channel pulse height}} = 0.91. \quad (2)$$

Using equation 1 to determine the ratio of pulse
heights, we get:

$$\frac{H_1}{H_2} = \frac{R_2 + Z_0}{R_1 + Z_0} = 0.91, \quad (3)$$

where R_1 is the single channel discharge resistance
and R_2 is the dual channel discharge resistance. By
assuming that the resistance of a dual channel dis-
charge is equal to the parallel resistance of two
single channels (i.e. that $R_2 \simeq 0.5R_1$); we obtain
from equation 3 that $R_1 \simeq 1.3\ \Omega$. This value agrees
well with the value of resistance obtained using the
Spitzer resistivity for the arc channel.[3] An esti-
mate of risetimes can also be obtained using
equation 1. The 0-90% risetimes are:

$$\tau_1 = \text{single channel risetime} = \frac{2.3 L_{S1}}{R_1 + Z_0}$$

$$(5)$$

$$\tau_2 = \text{dual channel risetime} = \frac{2.3 L_{S2}}{R_2 + Z_0}$$

where L_{S1} is the single channel switch inductance and
L_{S2} is the dual channel switch inductance. In order
to estimate the current risetime, L_{S1} and L_{S2} must be
estimated. The inductance of the electrodes, L_e, can
be estimated by modeling the spark gap as a coaxial
inductor. The estimated inductance of the electrodes
is then :

$$L_e = 62\ \text{nH}.$$

Likewise, the inductance of a single arc channel can
be estimated by assuming that the arc channel has a
diameter of 0.1 mm. The estimated inductance of a
single arc is 33.7 nH. According to reference 4, the
inductance of a two channel discharge is related to
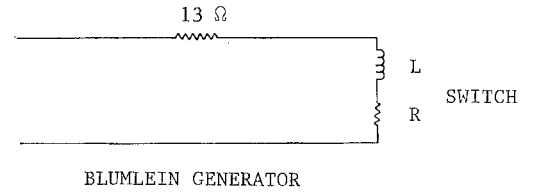the inductance of a one channel discharge by:

BLUMLEIN GENERATOR

Fig. 8   Circuit Model used for Calculating the
         Current Pulse Rise Time

$$L_2 = .66\ L_1.$$

Thus, the estimated inductance of a two channel dis-
charge is 22.24 nH. With these estimates, L_{S1} and L_{S2}
can be estimated:

$$L_{S1} = 62 + 33.7 = 95.7\ \text{nH}$$

$$L_{S2} = 62 + 22.24 = 84.24\ \text{nH}.$$

According to equation 5, the risetimes would then be:

$$\tau_1 = 30.15\ \text{ns}$$

$$\tau_2 = 29.14\ \text{ns}$$

and the ratio of risetimes is:

$$\frac{\tau_2}{\tau_1} = .97.$$

These results are in excellent agreement with the
measured results.

IV Conclusion

From the experiments, we conclude that dual chan-
nel breakdown can be initiated by the low laser power
density transmitted by optical fibers. However, the
process, in the case of an overvolted gap, depends on
the relative importance of the space charge present at
the time of laser firing and on the gap polarity.
Since there is no space charge in an under volted gap,
it may be feasible to use this scheme to trigger such
a gap. However, the delays and jitter observed here,
for the case of early laser firing time, indicate that
it may not be a practical possibility unless the fiber
transmitted power can be increased. This may be done,
at present, by increasing the number of fibers focused
on each channel.

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